Copy 1

RM No. A9C09

NACA RM No. A9C09

3 1176 00115 0839

NACA

RESEARCH MEMORANDUM

A REVIEW OF INSTRUMENTS DEVELOPED FOR THE MEASUREMENT OF THE METEOROLOGICAL FACTORS CONDUCIVE TO AIRCRAFT ICING

By Alun R. Jones and William Lewis

Ames Aeronautical Laboratory
Moffett Field, Calif.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON
April 26, 1949

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

A REVIEW OF INSTRUMENTS DEVELOPED FOR THE MEASUREMENT OF THE METEOROLOGICAL FACTORS CONDUCIVE TO AIRCRAFT ICING

By Alun R. Jones and William Lewis[1]

SUMMARY

The status of instruments suitable for the measurement of the meteorological factors conducive to aircraft icing is reviewed. The meteorological factors to be evaluated are listed, and tentative values for the desired and acceptable accuracy of measurement for each factor are suggested.

Nine instruments which appear to be the most promising for the procurement of the meteorological data are discussed with respect to the quantities they measure, principle of operation, range and accuracy, duration of a single reading, and advantages and disadvantages associated with their use. Recommendations are presented for the continued research and development of icing meteorological instruments.

INTRODUCTION

The design of thermal ice-prevention equipment for airplanes has progressed to a state where a knowledge of the physical characteristics of icing clouds is required (references 1 and 2). Considerable flight research in natural icing conditions has already been accomplished by the NACA with the aim of providing the necessary data. Some of the NACA results obtained in this field are presented in references 3 and 4, and reference 5 presents a discussion of the important meteorological factors conducive to aircraft icing and suggests values for these factors to be considered in the design of ice-prevention equipment.

---

[1]Meteorologist, U. S. Weather Bureau, assigned to the Ames Aeronautical Laboratory for collaboration on NACA icing research.

Although the research which has been completed provides a good basis for an initial understanding of the physical characteristics of icing conditions, considerably more meteorological data must be obtained in order to establish, with reasonable accuracy, the probable ranges and relative frequencies of values of the pertinent factors. One of the most serious problems encountered in the investigation of the meteorological factors conducive to aircraft icing has been the procurement of suitable instrumentation. For basic or fundamental research in the field, the principal physical characteristics of an icing cloud which, ideally, would be measured continuously and simultaneously may be listed as (1) liquid-water content, (2) free-air temperature, (3) altitude, (4) average drop diameter, (5) maximum drop diameter, and (6) drop-size distribution. Filling out the framework established by the results of the basic research will require the procurement of data in sufficient quantities to be applicable to statistical analysis. For such a statistical investigation, a continuous, correlated record of liquid-water content, free-air temperature, and altitude would represent the minimum requirements. The addition of a recording of average drop diameter to these three items would be very desirable, and the further addition of recorded maximum drop size would complete the statistical picture.

This report presents the results of a review of available meteorological instruments, or measurement techniques, to segregate those devices which had either produced the best results or showed the most promise. It was originally prepared for the Oct. 18, 1948 meeting of the NACA Subcommittee on Icing Problems, for the purpose of establishing the status of the development of icing meteorological instruments and to serve as a basis for recommendations concerning future development. In its present form, the report incorporates the helpful comments of the Subcommittee members. Appreciation is also extended to Dr. H. G. Houghton of the Massachusetts Institute of Technology and Dr. Vincent J. Schaefer of the General Electric Company for providing suggestions and information during the preparation of the initial report for the Subcommittee. In several instances, the comments by Dr. Houghton and Dr. Schaefer constituted the main source of information.

RANGE AND DESIRED ACCURACY

Estimated maximum values of the pertinent meteorological factors for various possible icing conditions are presented in table I of reference 5. A study of this table provides an indication of the required range of any proposed icing meteorological instrument.

The desired accuracy is somewhat difficult to state, since reliable meteorological instruments are not available in sufficient quantity to allow the investigator to be exacting. In order to provide an approximate yardstick of the order of accuracy that is considered necessary and reasonable, however, two values will be assigned to each of the pertinent meteorological factors. The first value, termed "acceptable," represents the estimated maximum tolerable error that an instrument could have and still provide useful data. The second value termed "desirable" represents the minimum error that appears reasonable and practical to specify, considering the limitations of existing instruments, human errors, and present intended use of the data.

Item	Basic research		Statistical data	
	Acceptable accuracy	Desirable accuracy	Acceptable accuracy	Desirable accuracy
liquid-water content	±15%	±5%	±25 %	±10%
free-air temperature	±3° F	±1° F	±5° F	±2° F
altitude	±300 ft	±100 ft	±500 ft	±200 ft
average drop diameter	±30%	±10%	±35 %	±10%
maximum drop diameter	±30%	±10%	±40 %	±10%
[1]drop-size distribution, σ/d_{av}	±30%	±10%	±50 %	±15%

[1] $\dfrac{\sigma}{d_{av}} = \dfrac{\text{root-mean-square deviation of volume distribution}}{\text{average drop diameter based on volume of drops}}$

REVIEW OF CURRENTLY AVAILABLE INSTRUMENTS AND MEASUREMENT METHODS

The following pages present a review of the nine most promising icing instruments. Wherever possible, a picture of the instrument under consideration has been included. The instrument descriptions have been minimized, but in each case a reference which contains the detailed information has been listed.

Rotating Cylinders

Factors measured.- The meteorological factors which can be computed from rotating-cylinder data are liquid-water content, mean-effective drop diameter,[2] and drop-size distribution.

Principle of operation and description.- Operation of the instrument is based on the fact that when a cylinder moves through a cloud, the amount of water intercepted per unit projected area is dependent on the diameter of the cylinder and the size of the cloud drops. The collection efficiency of cylinders, defined as the ratio of the amount of water intercepted to the amount of water originally contained in the volume swept out, has been calculated (reference 6) and is thus a known function of drop diameter, cylinder diameter, airspeed, temperature, and pressure. Collection efficiency increases with increasing drop diameter, decreasing cylinder diameter, and increasing airspeed. By means of these relationships, the liquid-water content, mean-effective drop diameter, and drop-size distribution can be calculated from the weights of ice collected during the simultaneous exposure of a series of cylinders of different diameters. The methods of calculation are described in references 6 and 7.

The rotating-cylinder instrument used by the Ames Aeronautical Laboratory was comprised of four cylinders of 3-, 1-1/4-, 1/2-, and 1/8-inch diameters, each 5 inches long. (See fig. 1.) The cylinders were joined together coaxially and the complete unit was extended into the air stream and rotated at about 20 revolutions per minute during a measured exposure period. After exposure the assembly was disassembled and the cylinders stored separately in airtight containers which were later weighed to determine the amount of ice collected.

Range and accuracy.- Although the rotating-cylinder instrument provides data from which the liquid-water content, mean-effective drop diameter, and drop-size distribution can all be evaluated, the accuracy with which each factor is determined is different. In general, the method provides good average values of liquid-water content, good to fair values of mean-effective drop diameter, and fair to unusable values of drop-size distribution.

The calculation of liquid-water content is accomplished by an extrapolation from the values of water intercepted per unit area to obtain the rate of water interception for a body having a collection efficiency of 100 percent. The amount of extrapolation is small since the collection efficiency of the 1/8-inch cylinder is over 90 percent in most cases. Moreover, the curves from reference 6

[2]The amount of water in all of the drops of a diameter greater than the mean-effective drop diameter is equal to the amount of water in all of the drops of smaller diameter.

provide a sound basis for the extrapolation, hence the resulting values of liquid-water content are reliable and fairly accurate over the entire range of conditions encountered in icing clouds. It is estimated that the four-cylinder apparatus as employed by the Ames Aeronautical Laboratory provides values of average liquid-water content accurate to ±5 percent. The agreement between this average value and the actual value at any instant is, of course, dependent upon the uniformity of the cloud.

The mean-effective drop diameter is determined from the variation of amount of water intercepted per unit area with cylinder diameter, hence the accuracy of the result depends on the amount of this variation. For small values of drop diameter the variation is considerable but as the drop size increases and the collection efficiency of all of the cylinders approaches unity, the variation in collection efficiency with cylinder diameter becomes smaller. The useful range of the instrument is limited to values of drop diameter for which the difference between the amount of water intercepted per unit area by the largest and smallest cylinders is significantly greater than the error in the determination of the amount of water intercepted by each cylinder.

In order to obtain an indication of the order of magnitude of the effect of actual drop diameter on the accuracy of measurement of drop diameter, calculations have been made based on the physical dimensions (3-, 1-1/4-, 1/2-, and 1/8-inch diameters) of the Ames Aeronautical Laboratory apparatus. These calculations were based on the assumption of a maximum error of ±5 percent in the determination of the amount of water intercepted by each cylinder. The results are presented as curve A in figure 2 which represents the maximum error to be expected in the determination of mean-effective drop size if the water interceptions can be relied upon to ±5 percent. It is seen that the percentage error increases with an increase in the actual mean-effective drop size; for example, in the most commonly experienced drop-diameter range in icing conditions (10 to 20 microns) the maximum error in the determination of mean-effective drop diameter would range from 4 to 9 percent; whereas for the larger drop sizes (40 microns) a maximum error of 30 percent would result.

The error in the determination of mean-effective drop diameter by the rotating-cylinder method can be reduced by increasing the diameters of the cylinders, and thus providing a larger spread to the values of weight of water intercepted per unit projected area of cylinder. Curve B of figure 2 presents the calculated error for four cylinders all twice the diameter of the Ames Aeronautical Laboratory cylinders, and again based on the assumption of a

5-percent error in the measurement of the weight of water intercepted. It can be shown that for a given desired accuracy, which would be obtained with a specified set of cylinders for a mean-effective diameter of D, the same accuracy can be obtained at $D\sqrt{2}$ if the cylinder sizes are doubled. Thus, 10-percent accuracy at 22 microns (curve A, fig. 2) can be increased to 10-percent accuracy at 31 microns ($22\sqrt{2}$) by doubling the cylinder size (curve B, fig. 2). For accurate measurement above 35 microns it would appear that the diameter of the largest rotating cylinder should be greater than 3 inches.

The drop-size distribution is determined by a comparison of the shape of the curve obtained by plotting the logarithm of the rate of water interception per unit area against the logarithm of the cylinder diameter with a set of theoretical curves calculated for five different arbitrarily specified drop-size distributions. (See reference 6.) Since the data points are somewhat scattered and frequently can be fitted to several of the calculated curves with equal facility, the method does not represent a precise means for the determination of drop-size distribution.

Duration of a single reading.- Experience indicates that an exposure time of 1 to 5 minutes appears to be a reasonable compromise between the desirability of collecting enough ice to reduce weighing errors (percentage) and collecting too much which changes the cylinder size, and possibly the shape.

Advantages.-

1. The rotating cylinder technique represents the most accurate and dependable method for the determination of liquid-water content and mean-effective drop size derived to date.

2. The cylinders collect ice in the same manner as airplane components so that, even if the absolute values of the data are incorrect, they are still useful qualitatively for design purpose, provided everyone uses the same basis.

3. Operation of the rotating cylinders is very reliable because of the lack of technical complexity.

4. The method is adaptable to flight use.

Disadvantages.-

1. Analysis of the cylinder data provides an integrated record over the period of exposure; therefore, maximum

instantaneous values cannot be segregated from the results.

2. The method requires one operator full time.

3. Work-up of the data is somewhat laborious, and the results are not available until some time after the flights.

4. The cylinders and attendant apparatus are bulky and difficult to use in pressure cabins.

5. The method tends toward inaccuracy at mean-effective drop diameters above 35 microns unless quite large cylinders are used.

6. Drop-size-distribution data calculated from the cylinder data are unreliable. Checks made with four cylinders of equal size, as suggested in reference 4, show an average variation sufficient to make an actual B distribution (reference 6) appear as a D distribution.

Remarks.- The method has assumed the position of a standard against which other instruments are calibrated, and is apt to remain so until replaced by a device based on operating principles which are considered, or proved, to be more fundamental and reliable than the theory behind the rotating cylinders.

Fixed Cylinder

Factor measured.- The fixed cylinder is employed for the determination of the maximum drop diameter.

Principle of operation and description.- The area of impingement of water drops on a nonrotating cylinder is taken as an indication of the maximum diameter of the drops present. A large cylinder is used to assure a collection efficiency less than 100 percent. One form of the device consists of a 4-inch-diameter cylinder with blueprint paper stretched over the surface. (See fig. 3 and reference 3.) The cylinder is exposed for a brief period of time and the area of impingement, easily discernible on the blueprint paper, provides an indication of the maximum diameter of the drops which were present in sufficient quantity to leave a trace. Another form consists of a cylinder with markings on the surface which are used to estimate the extent of the ice accretion. The accretion is removed periodically by rotating the cylinder against a knife-edge scraper. (See fig. 4 and reference 4.)

Range and accuracy.– As discussed in reference 4, considerable discrepancy has been noted between the maximum drop diameter as indicated by the fixed cylinder and that computed from the rotating-cylinder data. This discrepancy is again present in the 1947–48 meteorological data obtained during the C-46 airplane icing operations by the Ames Aeronautical Laboratory and has not been resolved at the present writing. The most probable source of error in the determination of the maximum drop diameter by the fixed-cylinder method is the measurement of the extent of the ice accretion on the cylinder. This extent is commonly expressed as the included angle 2θ between the two radii of the cylinder which define the extremities of the ice accretion. To obtain an indication of the effect of an error in the determination of θ on the value of maximum drop diameter, calculations have been made for a 5-inch-diameter cylinder and an assumed maximum error of 5° in the value of θ. The result of these computations is presented as curve C in figure 2, which represents the maximum percent error in the maximum drop diameter for a 5° error in θ. On the basis of curve C in figure 2, it would appear reasonable to assign the following accuracies to a 5-inch fixed cylinder:

Actual maximum drop diameter (microns)	Maximum measurement error, (microns)
5 to 15	2
15 to 25	4
25 to 35	7
35 to 50	15

At the present time it appears that the principal source of error in the fixed-cylinder method as used at Ames Aeronautical Laboratory during 1948 (fig. 4) lies in the inability of the observer to detect the extreme edge of the ice formation. Another contributing factor is probably the effect of the slight change in profile due to the presence of the ice layer. Reasonable agreement between the rotating-cylinder and fixed-cylinder data may be obtained by adding a constant correction of 5° to the observed value of θ. These considerations suggest that the method of measuring the angle by means of a trace on blueprint paper (fig. 3) is more accurate and dependable than by visual observation of the ice formation. The range of the device is limited only by the practical aspect of the maximum cylinder size that can be employed in any projected investigation.

Duration of a single reading.– The form of the device shown in figure 3, using blueprint paper, requires an exposure period of from

2 to 30 seconds depending on the severity of the icing conditions. With the form shown in figure 4 a longer period, usually from 1 to 5 minutes, is required in order to allow the formation of sufficient ice to be observed visually.

Advantages.–

1. The method is based on reliable and simple theory.

2. The apparatus is mechanically simple, and easy to operate, so a record is practically assured.

Disadvantages.–

1. Recording of the data from the fixed cylinder requires constant attention by the operator.

Remarks.– This device should give good values of maximum drop diameter, and the discrepancy between its indications and those from the rotating cylinders should be eliminated as soon as possible in order that both can be used with confidence.

Rotating-Disk Icing-Rate Meter

Factor measured.– The rotating disk is utilized for the continuous measurement of liquid-water content.

Principle of operation and description.– A thin disk about 2 inches in diameter, 1/8 inch thick at the center, and beveled to 1/32 inch at the edge is mounted with the plane of the disk parallel to the direction of the free stream. (See fig. 5.) The disk is rotated at about two revolutions per minute. The thickness of the ice accretion on the rim is continuously indicated by a feeler at the back of the disk and the accretion is then removed by a scraper located behind the thickness feeler. Observations of the profile of ice collected while the disk was stationary indicate that 95 percent of the ice is collected in an angle of 120°, thus the effective exposure time at a rotation rate of two rpm is about 10 seconds. On the Ames Aeronautical Laboratory instrument the feeler is located 144° from the forward point, giving rise to a lag of 12 seconds at two rpm. Use of a variable rate of rotation, for example, from one-third to five rpm, would give more accurate measurement of very low values of water content and a more detailed record during periods of heavy icing. The effective exposure time would then vary from 1 minute to 4 seconds. More detailed information is contained in references 7 and 8.

Range and accuracy.– The motion of the feeler is actually an indication of the rate of ice accretion on the rim of the disk. This indication can be converted to a continuous record of liquid-water content by assuming, or obtaining empirically, the ratio E/ρ where E represents the collection efficiency of the disk and ρ the density of the ice accretion. Based on 150 simultaneous readings of the rotating disk and the rotating cylinders, for the same exposure time, an average value of 1.1 for E/ρ has been established.[3] The drop-size range during these 150 readings varied from 8 to 50 microns. The value of 1.1 is an arithmetic average, with the root mean square deviation being 0.22 and the maximum deviation between 10 and 40 microns being 0.6. It should be pointed out that the measured values of E/ρ are influenced by errors in the rotating-cylinder observations and errors due to the difficulties in synchronization; hence, the actual variation of E/ρ is probably considerably less than indicated by these data. Based on these results it is believed that the use of a constant value of E/ρ equal to 1.1 would result in the computation of values of liquid-water content with a probable error of ±12 percent or less over the entire icing range of table I reference 5.

Duration of a single reading.– The rotating disk provides a continuous record of the average liquid-water content over an effective interval of about 10 seconds when operated at two rpm. When operated at variable speed, the effective exposure time should be adjustable from 1 minute to 4 or 5 seconds.

Advantages.–

1. The rotating-disk icing meter provides a continuous indication of liquid-water content with reasonable accuracy over the drop-diameter range associated with icing conditions.

2. The instrument is reliable and can be converted readily to a recording device.

3. The instrument is adaptable to flight use.

Disadvantages.–

1. The rotating-disk icing meter actually indicates rate of icing instead of the more desirable fundamental factor,

[3]Data obtained during the 1947–48 icing research flights conducted by the Ames Aeronautical Laboratory.

liquid-water content. Further verification of the independence of the device with respect to drop size, for all practical purposes, is desirable.

2. The lag of the instrument is somewhat large for the ideal determination of maximum instantaneous conditions.

Remarks.- This device holds more promise than any other currently available instrument for the statistical measurement of liquid-water content. The rotating disk could be used in conjunction with some device for the continuous recording of the average drop diameter (such as the visibility meter to be discussed later) to provide the basis for a statistical study of icing conditions. Dr. Houghton has indicated that the rotating disk with which he was familar did not possess the necessary ruggedness and reliability to qualify it as a statistical instrument. However, experience gained by the Ames Aeronautical Laboratory during the 1947-48 icing operations, with an instrument of somewhat different design from that used by Dr. Houghton, indicated that the device held considerable promise for the collection of statistical data. As purely a research instrument it is the most reliable development to date which could provide a detailed record of variations in liquid-water content.

Capillary Collector

Factor measured.- The capillary collector was developed for the determination of the liquid-water content of clouds.

Principle of operation and description.- A porous head is exposed to the cloud and, by the application of suction to the aft side of the head, water collecting on the forward side is drawn through the porous material. The relation between the amount of water passing through the head in unit time and the free-stream liquid-water content is established by calibration under controlled conditions. In the original collector, as conceived by Dr. B. Vonnegut of M.I.T., references 7 and 8, the rate of water collection was obtained by the visual observation of the movement of an air bubble in a calibrated capillary. In a more recent development of the instrument by the General Electric Company, references 9 and 10, the collected water is deposited on a continuously moving glass tape, impregnated with methylene blue dye powder. The width of the trace on the tape is proportional to the rate of water interception by the head. The General Electric instrument is shown in figure 6.

Range and accuracy.— The authors have had no personal experience with the use of the capillary collector. Drs. Houghton and Schaefer concur in stating that the instrument provides satisfactory and reliable readings in clouds above freezing. The specific range and accuracy of the data which lead to this common conclusion was not stated. Under icing conditions the collecting head requires heating which, in turn, introduces evaporative errors. Dr. Houghton describes these errors as serious. Dr. Schaefer does not mention the evaporative error specifically, but states, "We have not concerned ourselves with its operation under icing conditions because of the difficulties involved."

Duration of a single reading.— The instrument provides a continuous record of the liquid-water content.

Advantages.—

1. The capillary collector provides for the continuous automatic recording of liquid-water content at temperatures above freezing.

2. The instrument is relatively simple in operation and is dependable.

3. Accurate measurements at temperatures above freezing are provided.

4. The instrument is adaptable to flight use.

Disadvantages.—

1. Evaporative errors seriously complicate the use of the instrument in icing conditions.

Remarks.— At the present time the instrument represents a very useful research tool at temperatures above freezing. Thus, the use of the rotating disk below freezing and the capillary collector above freezing would provide a continuous record of variation in liquid-water content.

Rainbow Recorder

Factors measured.— The instrument was developed by the Ames Aeronautical Laboratory to provide a continuous record of liquid-water content, average drop diameter based on projected areas, and drop-size distribution.

Principle of operation and description.— The instrument is based on the rainbow-forming properties of water drops. A high-intensity, modulated beam of light is projected into the air stream containing droplets, and the rainbow produced is scanned by an oscillating mirror. The varying intensity of the rainbow light is recorded. From a plot of intensity against mirror angle, and the basic optical theory of the rainbow, values of liquid-water content, average drop diameter, and drop-size distribution can be computed. For the Ames instrument, figure 7 and reference 11, the rainbow scanning rate is 1/2 second.

Range and accuracy.— Theoretically, the instrument should be usable for the entire range of icing conditions in table I, reference 5. Actually, difficulties in operation have resulted in very few usable flight records. These problems are associated with excessive background light, and discontinuities in the cloud structure experienced in flight. During ground tests of the instrument, where the deleterious effects of background light and cloud variation have been eliminated or minimized, the records from the rainbow recorder have been much more encouraging than those obtained in flight. In one such test, the recorder was operated at night on a mountain in a fairly consistent fog. Photographs were taken of the drops to obtain drop size, and the liquid water was separated from a known quantity of the air by mechanical means. The results from these two procedures were in reasonably good agreement with those computed from the rainbow records. In another test, the instrument was operated in a darkened room containing a cloud formed by a water spray. Although the actual value of the liquid-water content and the drop size of the spray were not known, the rainbow recorder produced light-intensity curves of the general shape predicted by theory. It is estimated that basically the instrument could produce data in flight accurate to ±10 percent for average drop diameter and ±15 percent for liquid-water content if operation similar to that experienced in the cloud chamber could be achieved. Although the instrument is theoretically capable of measuring drop-size distribution, it is not considered likely that this can be achieved in practice.

Duration of a single reading.— The elapsed time for one complete record with the Ames Aeronautical Laboratory instrument is 1/2 second.

Advantages.-

1. Potentially, the instrument could provide, in flight, a continuous automatic recording of liquid-water content, and average area drop size.

2. The air stream is not disturbed by the instrument.

Disadvantages.-

1. The device is electrically complicated.

2. At the present scanning rate of the Ames Aeronautical Laboratory instrument (1/2 sec), the rate of variation of liquid-water content and drop size in some clouds precludes the procurement of a satisfactory record.

3. Variations in background light in clouds seriously affect the readings.

4. At present, the instrument requires continuous attention by personnel skilled in electronics.

5. The instrument with attendant apparatus is bulky.

Remarks.- Potentially, this is a very desirable instrument because so much information can be obtained from one record. It also has the advantage of not requiring any protuberance into the air stream. Although its present limitations restrict its immediate use for flight testing, the instrument might prove useful where these restrictions do not apply or are minimized; for example, for measuring liquid-water content and drop size for the flow of a relatively uniform cloud in a dark duct such as an icing wind tunnel, or the inlet ducting to a turbine engine in simulated icing tests. Under conditions of no background light a simple device based on a light source and a camera might suffice. In any further development of this type of instrument, an investigation of the corona rather than the rainbow might be profitable since the corona is 10,000 times as intense as the rainbow.

Dew-Point Recorder

Factor measured.- The dew-point recorder provides data from which the free-water content of a cloud can be calculated.

Principle of operation and description.— A representative sample of the cloud is inducted, heated to evaporate all of the free water (liquid water plus snow) present, and the dew point of the sample is measured. From this reading and the free-stream temperature, the free-water content of the air stream can be calculated. The dew-point recorder is designed to provide a continuous record of the dew point of the heated sample. The sample is caused to impinge on a mirror surface, the temperature of which is continuously regulated to maintain equilibrium conditions at the dew point. Control of the heating and cooling cycle is effected by utilizing the first signs of dew forming on the mirror surface as a signal to turn on the heating current. The surface temperature is measured with a thermocouple. Further details are available in reference 12, and the instrument of that reference is shown in figure 8.

Range and accuracy.— The accuracy with which liquid-water content can be computed from the dew-point recorder readings is directly proportional to the accuracy with which the difference between the free-air temperature and the dew point of the free-stream air can be measured. Experience in icing flights by the Ames Aeronautical Laboratory has shown that, for the relatively low values of liquid-water content associated with icing conditions, the required degree of accuracy of temperature measurement is prohibitive.

Duration of a single reading.— The instrument provides a continuous record.

Advantages.—

1. The instrument operates and records automatically.

Disadvantages.—

1. The accuracy required in the determination of the dew-point and free-air temperatures for the computation of liquid-water content in icing conditions is too great.

2. The dew point is not always clearly indicated, and is sometimes confused with the ice point.

3. Difficulties are encountered in obtaining a representative sample.

Remarks.— The percentage accuracy of this method of determination of free-water content decreases with the decrease of water content experienced as temperatures are reduced. The accuracy is not considered acceptable for measurements in icing conditions. The instrument produces reasonably accurate readings at temperatures above freezing and could prove useful in that range.

Visibility Meter

Factor measured.– This instrument measures the total projected area of cloud drops per unit volume of air, which is proportional to the ratio of the liquid-water content to the average drop diameter based on projected areas.

Principle of operation and description.– Operation is based on the degree of absorption of light by water drops in the path between a light source and a receiver. The reduction of illumination observed by the receiver is inversely proportional to the ratio of the average drop diameter based on projected area to the liquid-water content. If either of these quantities is measured simultaneously by other means, the other quantity can be obtained from the visibility meter record. An instrument based on the visibility principle is described in reference 13, and shown in figure 9.

Range and accuracy.– The authors have had no experience with this instrument. Dr. Houghton offers the following remarks: "This is basically a simple and reliable instrument. However, many problems arise in designing one suitable for use on aircraft. It should be particularly useful as an over-all check of dependable measurements of drop size and liquid-water content. If a satisfactory mechanical and electrical design can be achieved, it should be a reliable and useful research instrument. The time lag can be made very small and can be adjusted electrically to any desired value."

Duration of a single reading.– The instrument provides a continuous record.

Advantages.–

1. A continuous record is supplied automatically.

2. Operation of the instrument is based on simple principles.

Disadvantages.–

1. An indication of the ratio between two factors is provided, while the absolute values of each factor are the more desirable quantities to measure.

2. The device is moderately complicated electrically.

Remarks.– The main value of this instrument lies in its potential use in conjunction with some continuously recording liquid-water content device (such as the rotating disk) in the statistical determination of liquid-water content and average drop size. The instrument might also prove useful as an independent check on other instruments used to provide liquid-water content and drop-size readings.

Sooted Slides

Factor measured.– The sooted-slide technique is used primarily for the determination of drop-size distribution.

Principle of operation and description.– A small glass slide covered with soot is momentarily exposed to free-stream conditions. Drops impinging on the slide leave a trace and the drop diameters are calculated from this record. The time of exposure is very short, in the order of 1/100 second. One device used in flight (reference 7) for exposing the sooted slide to the air stream is shown in figure 10. In this device a sooted slide about 3/16 inch square is supported (by means of a special mount not shown in fig. 10) in the cylindrical cavity between the jaws of the shutter. The instrument is held in the air stream and the trigger pulled. The jaws then quickly open and close, exposing the slide for an instant to the air stream. Further information on the details of the sooted-slide method, and representative photographs of drop-impingement traces are available in references 7 and 14.

Range and accuracy.– The accuracy has not been established because the relationship between the sooted-slide traces and the size of the drops making the traces, even under laboratory conditions, is not completely established. The influence of the velocity of the drop at impact on the resultant trace requires further investigation.

Duration of a single reading.– The time of exposure of the slide to the air stream is very small, and can be considered as instantaneous.

Advantages.-

1. The sooted-slide technique represents one of few methods available for measuring drop-size distribution.

2. The method presents a quick means of making a spot check of drop diameters.

3. The method is simple in operation.

Disadvantages.-

1. Drops larger than 20 microns splash upon impact and do not leave a measurable trace.

2. The method is inaccurate at high velocities.

3. Evaluation of the data is very tedious.

Remarks.- Obtaining traces of water-drop impingements on a sooted slide represents a simple and useful technique for the determination of representative drop diameters under the proper conditions. The method, however, does not represent a satisfactory answer to the need for determining drop sizes in flight.

Drop Photography

Factors measured.- Drop photography is used primarily for the determination of drop-size distribution.

Principle of operation and description.- A representative sample of the cloud is photographed with a high-speed camera. The exposure on the film is actually the shadow of the drop rather than a picture of the drop itself. Because of the speed of the drops. the record will be a line image with currently available light sources unless a rotating prism is inserted in the optical system. Such a prism was used by the Canadian National Research Council who pioneered the photographing of cloud droplets in flight. (See reference 15.) The National Research Council equipment is shown in figure 11. In figure 11(b) the light source unit is visible below the fuselage just ahead of the nose wheel.

Range and accuracy.- The writers have no experience with this method of measuring drop-size distribution. Dr. Houghton offers the following: "The line images are acceptable if they are not too long. At the magnification necessary to resolve the small drops, the focal volume is very small as is also the depth of focus. In order to avoid errors due to drops outside the focal volume, the illumination should be confined to the focal volume. This is difficult but not totally impossible. The final straw is that the number of drops in the focal volume at any one instant is of the order of 1 to 10 and, hence, a great number of photographs is required to secure sufficient data for a drop-size distribution. For these reasons, we discarded this technique many years ago."

Duration of a single reading.– A reading may be obtained practically instantaneously.

Advantages.–

1. Drop photography probably represents the most direct method of determining drop-size distribution.

2. Operation of the photographic equipment is normally a simple procedure.

Disadvantages.–

1. A large number of photographs are required.

2. Evaluation of the data is very lengthy and tedious.

3. The photographic equipment is somewhat bulky.

Remarks.– Although attractive at first sight, the method has latent difficulties. Lack of other reliable methods of determining drop-size distribution may necessitate use of this method, but the development of alternate methods should be encouraged.

Note on the Effect of Increased Flight Speed on the Foregoing Remarks

Attention is directed to the fact that the foregoing discussion of icing instruments is based entirely on experience at flight speeds below 200 miles an hour. If icing encounters at speeds above this value are proposed, the possible effects on the operation of the icing instruments should be considered. Instruments such as the rainbow recorder and visibility indicator are probably not affected to any appreciable extent. The cylinders and rotating disk, however, would probably experience a blow-off of drops at increased speeds with resultant errors. The possible effects of compressibility and adiabatic heating should also be considered.

RECOMMENDATIONS FOR CONTINUED RESEARCH AND DEVELOPMENT OF ICING INSTRUMENTS

A review of the present status of research on the meteorological factors conducive to aircraft icing reveals two outstanding needs: (1) means for the continuous indication or recording of simultaneous values of liquid-water content, free-air temperature, altitude, and, if possible, average and maximum drop size; and (2) means for the statistical determination of liquid-water content, free-air temperature, altitude, average drop size, and, if possible, maximum drop size. The first need is a basic research requirement to supply further data on instantaneous values of the icing parameters in order that the instantaneous and intermittent icing classes (see table I, reference 5) can be more accurately specified. The second requirement is to provide a broader basis for the specification of icing parameters than was available in the preparation of reference 5. To satisfy these needs the following recommendations are presented:

1. Development of the rotating disk should be continued. This device should prove very useful in both the formative and statistical investigations just discussed, since it gives evidence of being capable of producing a continuous record of liquid-water content, with small lag, practically independent of drop size.

2. The visibility meter should be investigated as a possible statistical instrument for use with the rotating disk to provide average drop-size information.

3. Development of the rainbow recorder as a potential single instrument for providing both liquid-water content and drop-size data should be continued.

4. A reliable method for the measurement of drop-size distribution should be developed.

Ames Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Moffett Field, Calif.

REFERENCES

1. Jones, Alun R., Holdaway, George H., and Steinmetz, Charles P.: A Method for Calculating the Heat Required for Windshield Thermal Ice Prevention Based on Extensive Flight Tests in Natural Icing Conditions. NACA TN No. 1434, 1947.

2. Neel, Carr B., Jr., Bergrun, Norman R., Jukoff, David, and Schlaff, Bernard A.: The Calculation of the Heat Required for Wing Thermal Ice Prevention in Specified Icing Conditions. NACA TN No. 1472, 1947.

3. Lewis, William: A Flight Investigation of the Meteorological Conditions Conducive to the Formation of Ice on Airplanes. NACA TN No. 1393, 1947.

4. Lewis, William, Kline, Dwight B., and Steinmetz, Charles P.: A Further Investigation of the Meteorological Conditions Conducive to Aircraft Icing. NACA TN No. 1424, 1947.

5. Jones, Alun R., and Lewis, William: Recommended Values of Meteorological Factors to be Considered in the Design of Aircraft Ice-Prevention Equipment. NACA TN No. 1855, 1949.

6. Langmuir, Irving, and Blodgett, K. B.: A Mathematical Investigation of Water Droplet Trajectories. General Electric Research Laboratory Report. Contract W-33-038-ac-9151. Dec. 1944 – July 1945.

7. Vonnegut, B., Cunningham, R. M., and Katz, R. E.: Instruments for Measuring Atmospheric Factors Related to Ice Formation on Airplanes. M.I.T. De-Icing Research Laboratory Report. Contract No. W-33-038-ac-5443. Apr. 1946.

8. Katz, R. E., and Cunningham, R. M.: Instruments for Measuring Atmospheric Factors Related to Ice Formation on Airplanes – II. Aircraft Icing Instruments. M.I.T. De-Icing Research Laboratory Report. Contract No. W-33-038-ac-14165. Mar. 1948.

9. Schaefer, Vincent J.: The Liquid Water Content of Summer Clouds on the Summit of Mt. Washington. General Electric Research Laboratory Report. Contract W-33-038-ac-9151. Apr. 1946.

10. Falconer, R. E., and Schaefer, V. J.: A New Plane Model Cloud Meter. General Electric Research Laboratory Occasional Report No. 2, Project Cirrus. Contract No. W-36-039-SC-32427. May 15, 1948.

11. Malkus, Willem V. R., Bishop, Richard H., and Briggs, Robert O.: Analysis and Preliminary Design of an Optical Instrument for the Measurement of Drop Size and Free-Water Content of Clouds. NACA TN No. 1622, 1948.

12. Friswold, Frank A., Lewis, Ralph D., and Wheeler, R. Clyde, Jr.: An Improved Continuous-Indicating Dew-Point Meter. NACA TN No. 1215, 1947.

13. Orthel, John C.: Visibility Indicator. Aeronautical Ice Research Laboratory Report, serial number AIRL 6034 48-14-7. Mar. 1948. Prepared under contract W-33-038-ac-18024 for Air Materiel Command, U. S. Air Force, Wright Field, Dayton, Ohio

14. Schaefer, Vincent J.: The Preparation and Use of Water Sensitive Coatings for Sampling Cloud Particles. General Electric Research Laboratory Report. Contract W-33-038-ac-9151. Apr. 1946.

15. Elliott, H. W.: Cloud Droplet Camera. National Research Laboratories Report No. M.I.-701. National Research Council of Canada, Ottawa, Canada. Dec. 1947.

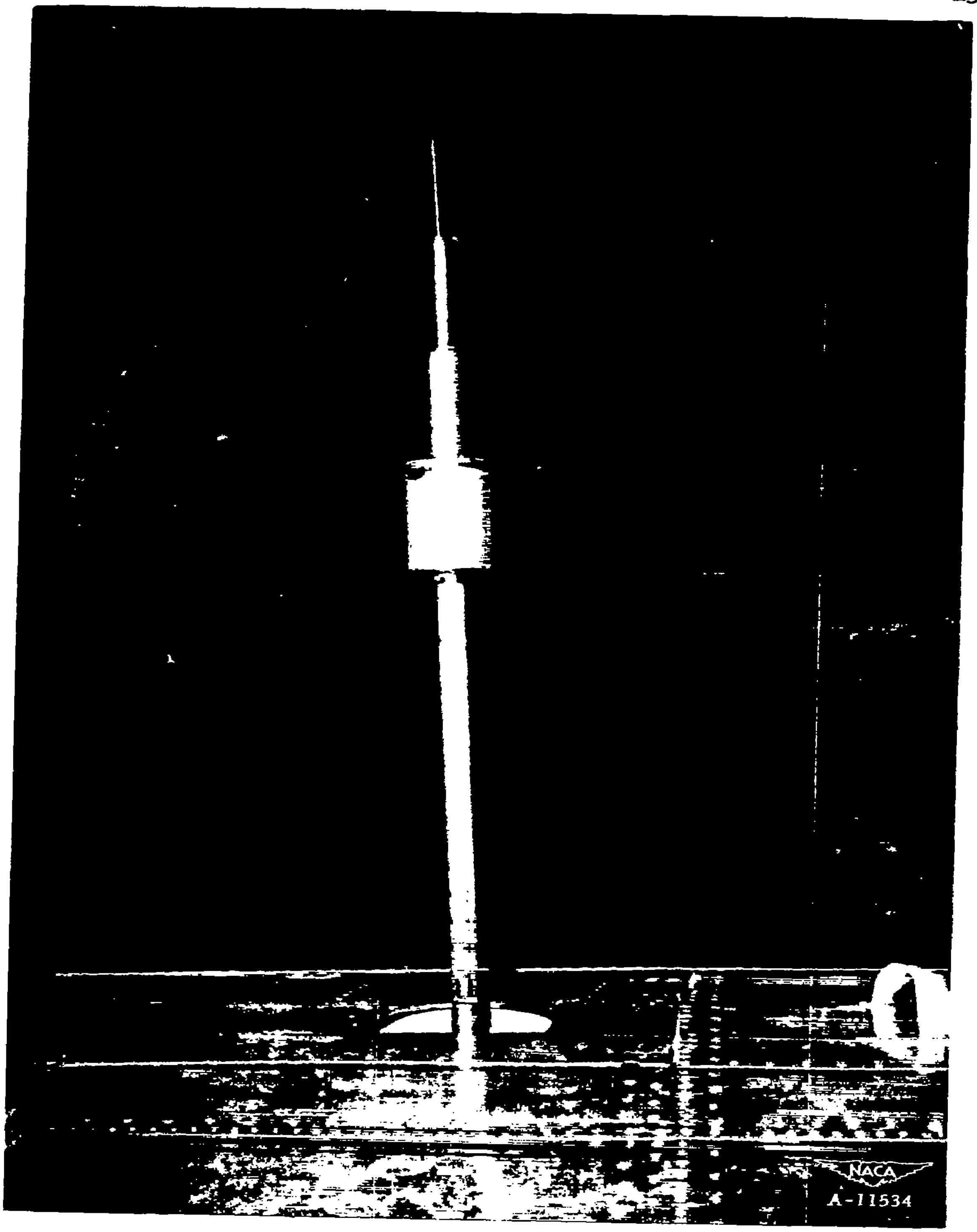


Figure 1.— Rotating-cylinder apparatus for the measurement of liquid-water content and drop size during flight in icing clouds.

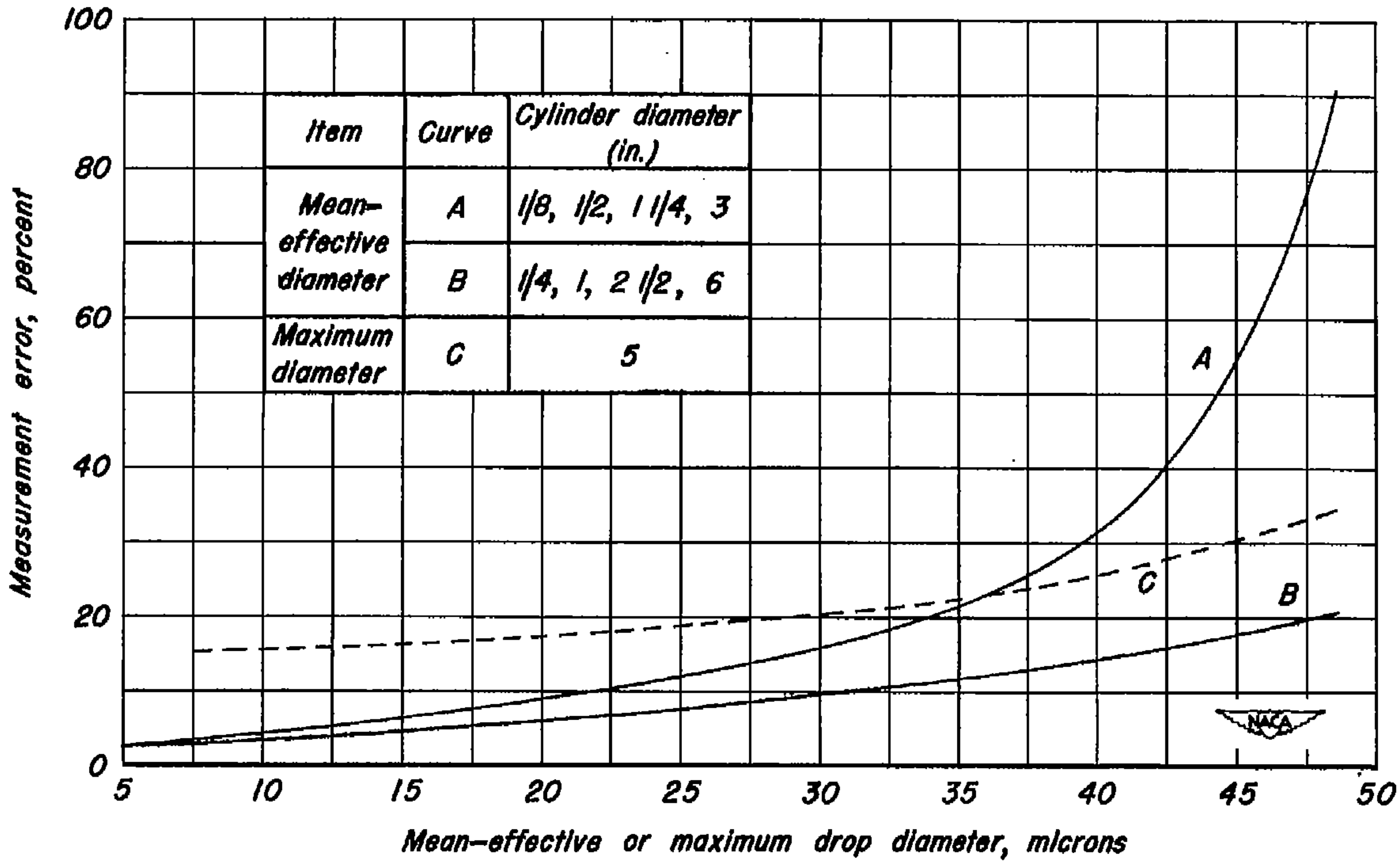


Figure 2.- Calculated error in the measurement of mean-effective drop diameter with four rotating cylinders, and maximum drop diameter with one nonrotating cylinder. Calculations based on assumption of errors of ± 5 % in determining the weight of ice accretions on the rotating cylinders, and +5° in the determination of the angle of water impingement (θ_m) on the nonrotating cylinder.

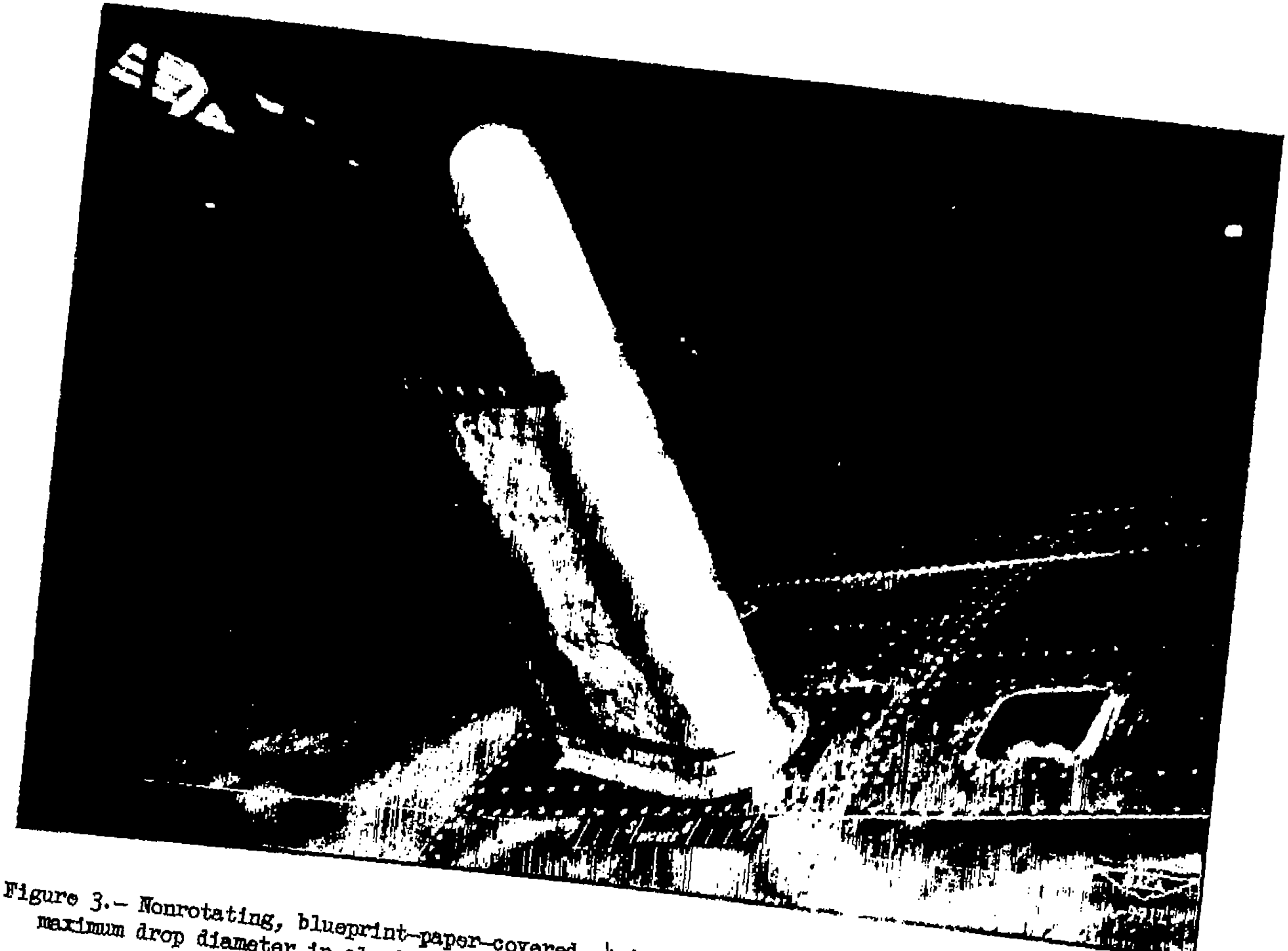


Figure 3.- Nonrotating, blueprint-paper-covered, 4-inch-diameter cylinder for the measurement of maximum drop diameter in clouds.

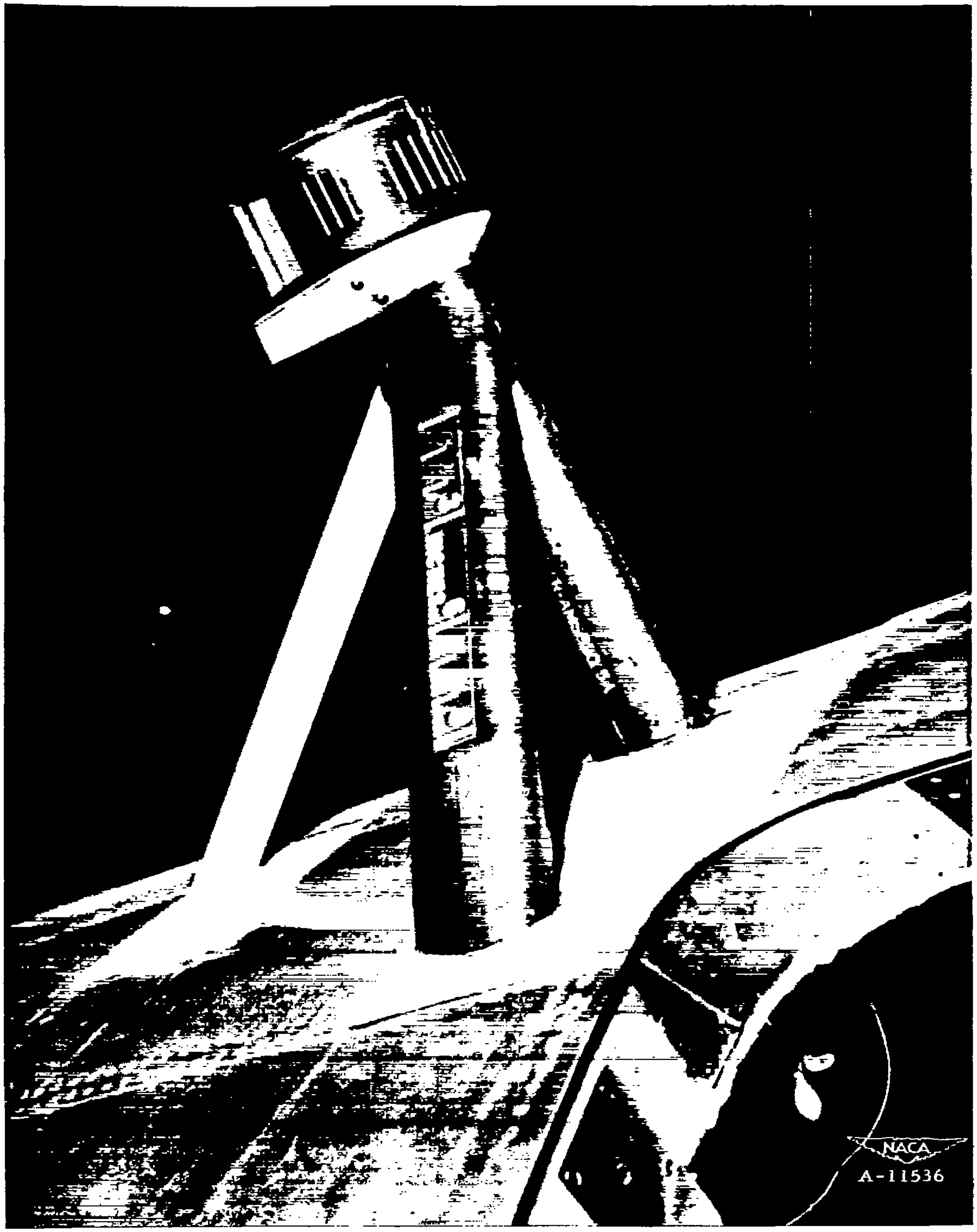


Figure 4.— Nonrotating, 5-inch-diameter cylinder for the measurement of maximum drop diameter in icing clouds.

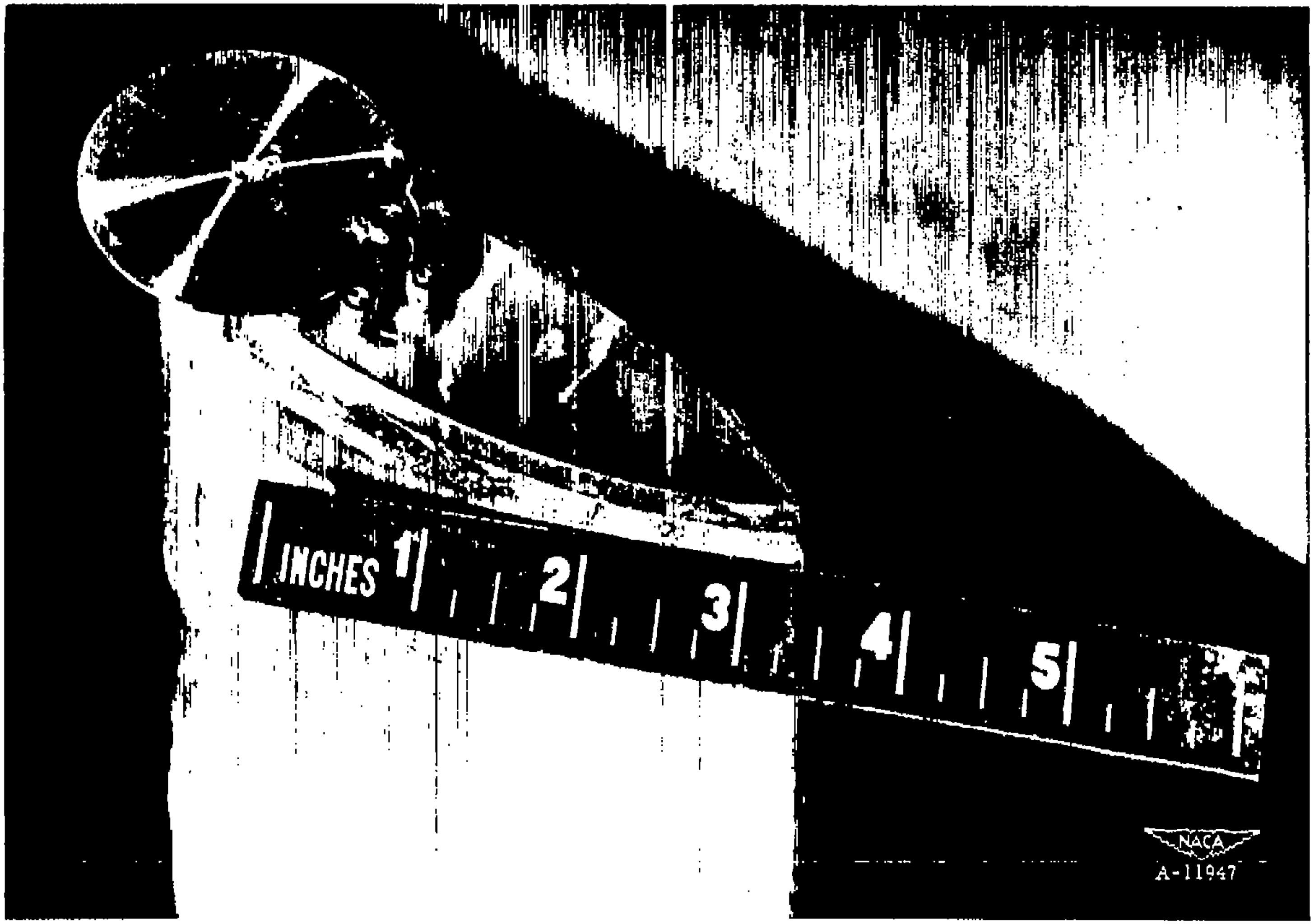


Figure 5.— Rotating disk for the measurement of liquid-water content in icing clouds. Note ice-thickness feeler and ice-removal scraper behind disk.

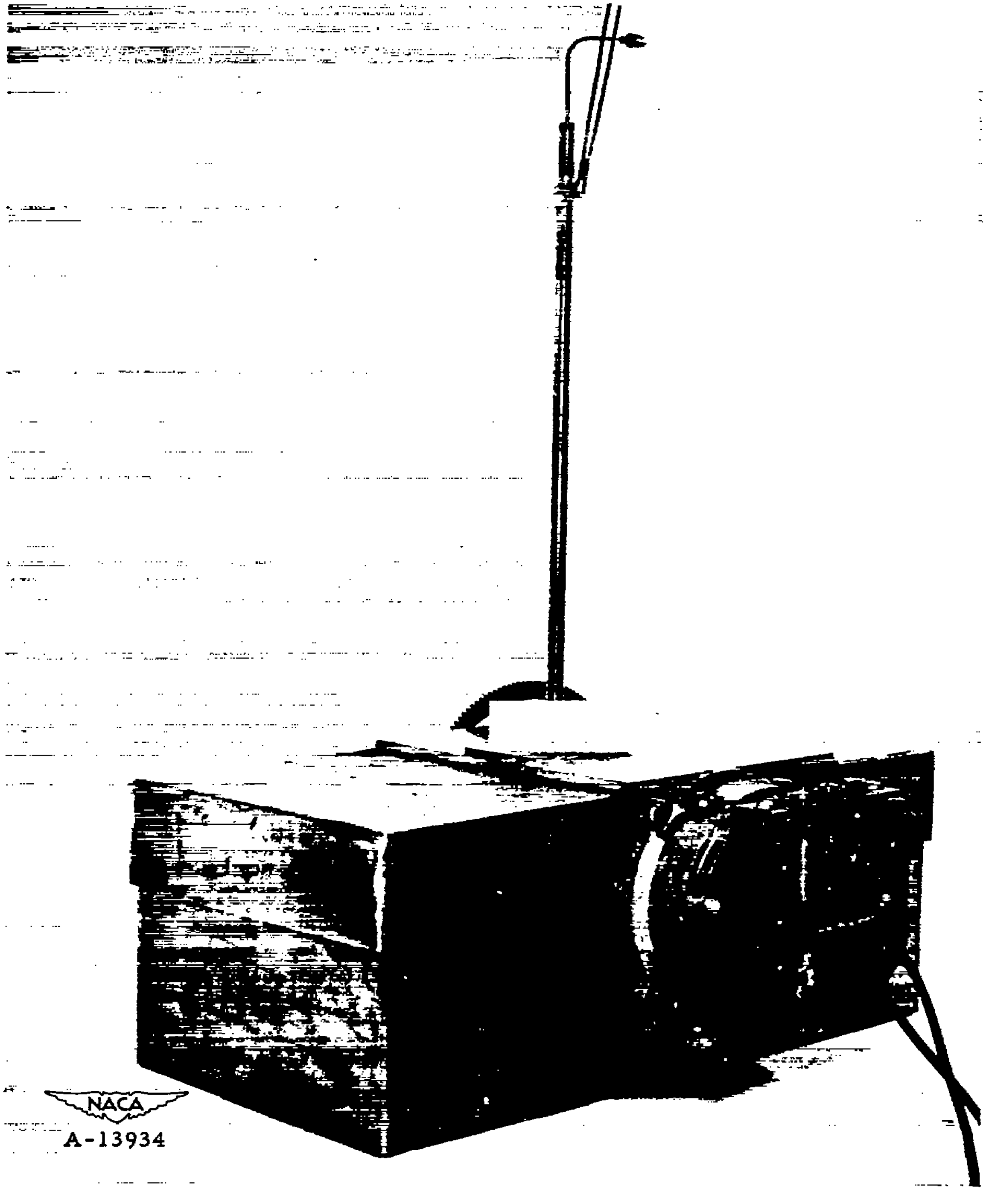
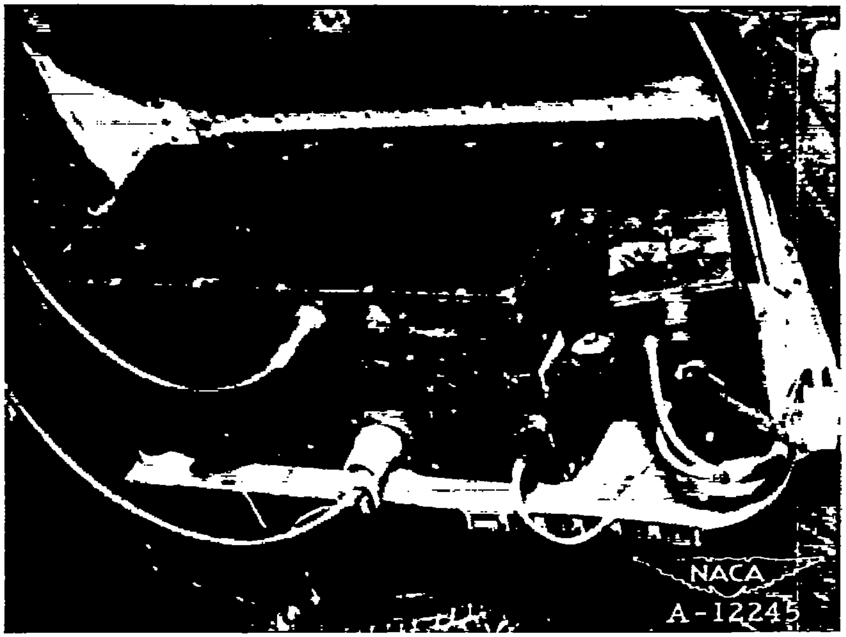
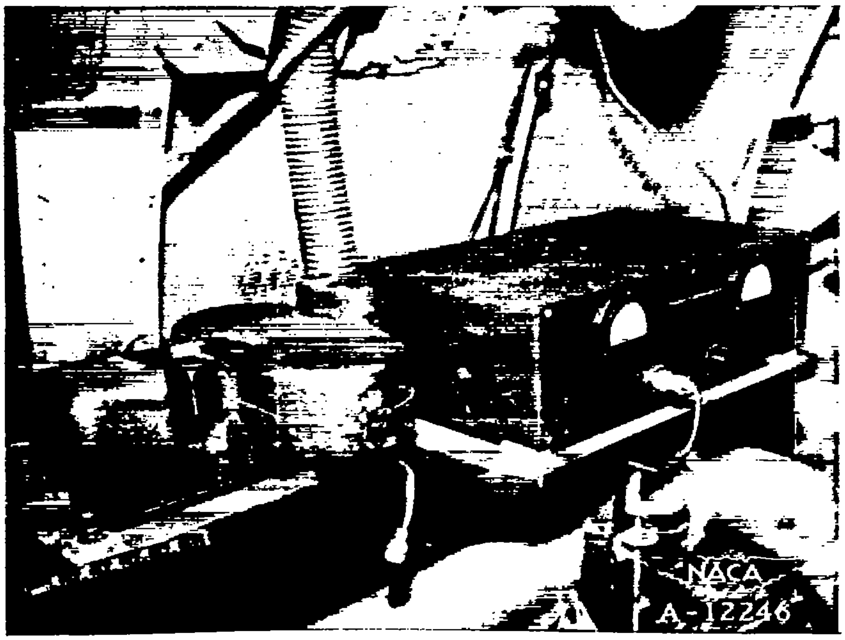


Figure 6.– The capillary collector for the measurement of liquid-water content in clouds. Photograph reproduced from reference 10 through courtesy of the U. S. Air Force.



(a) Light source, mirror, and photocell.



(b) Amplifier and recording galvanometer.

Figure 7.– The rainbow recorder used for measurement of liquid-water content and drop size in clouds.

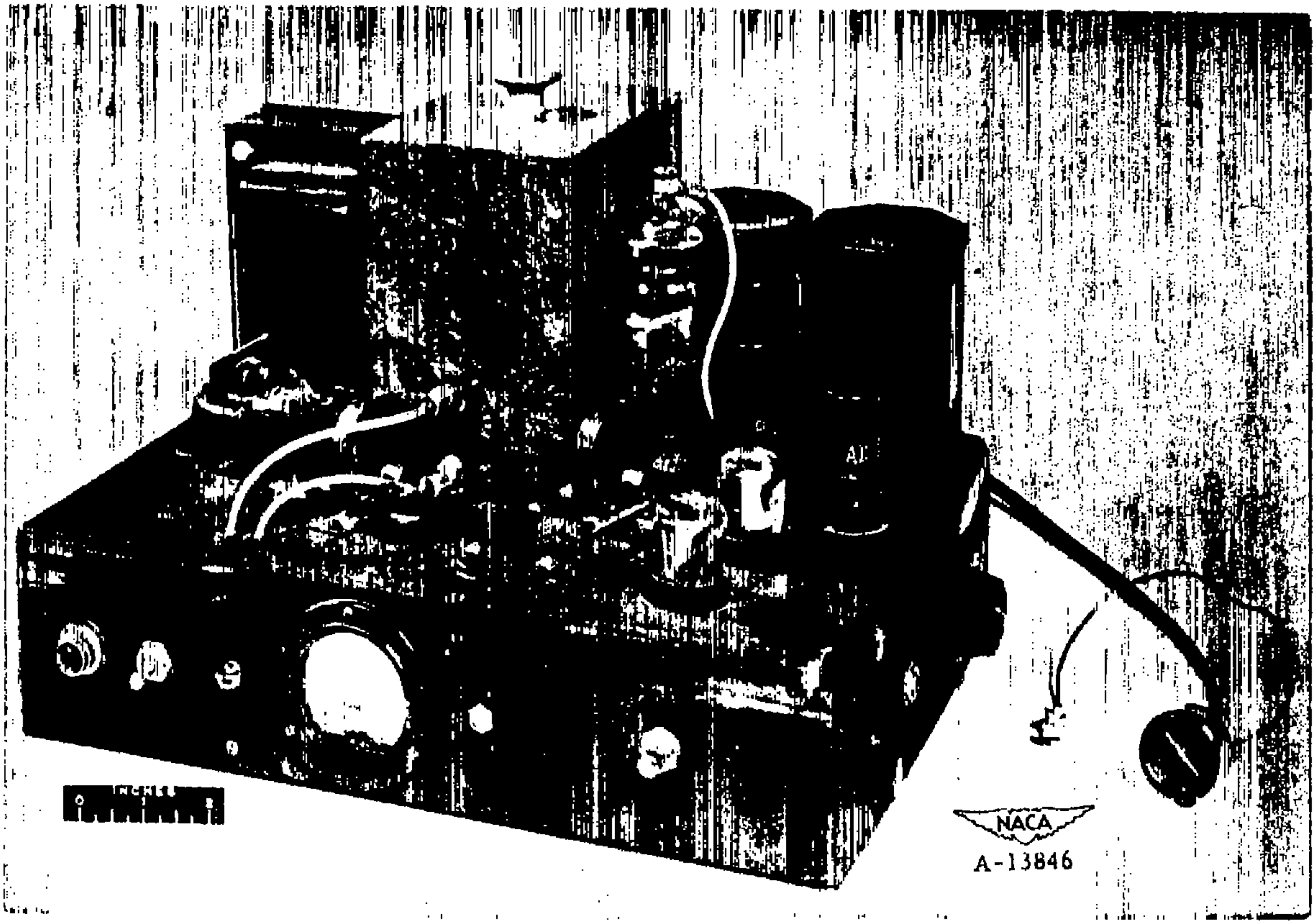


Figure 8.– Dew-point meter used for the determination of liquid-water content in clouds by calculations based on the dew-point and actual temperatures of the free-stream air.

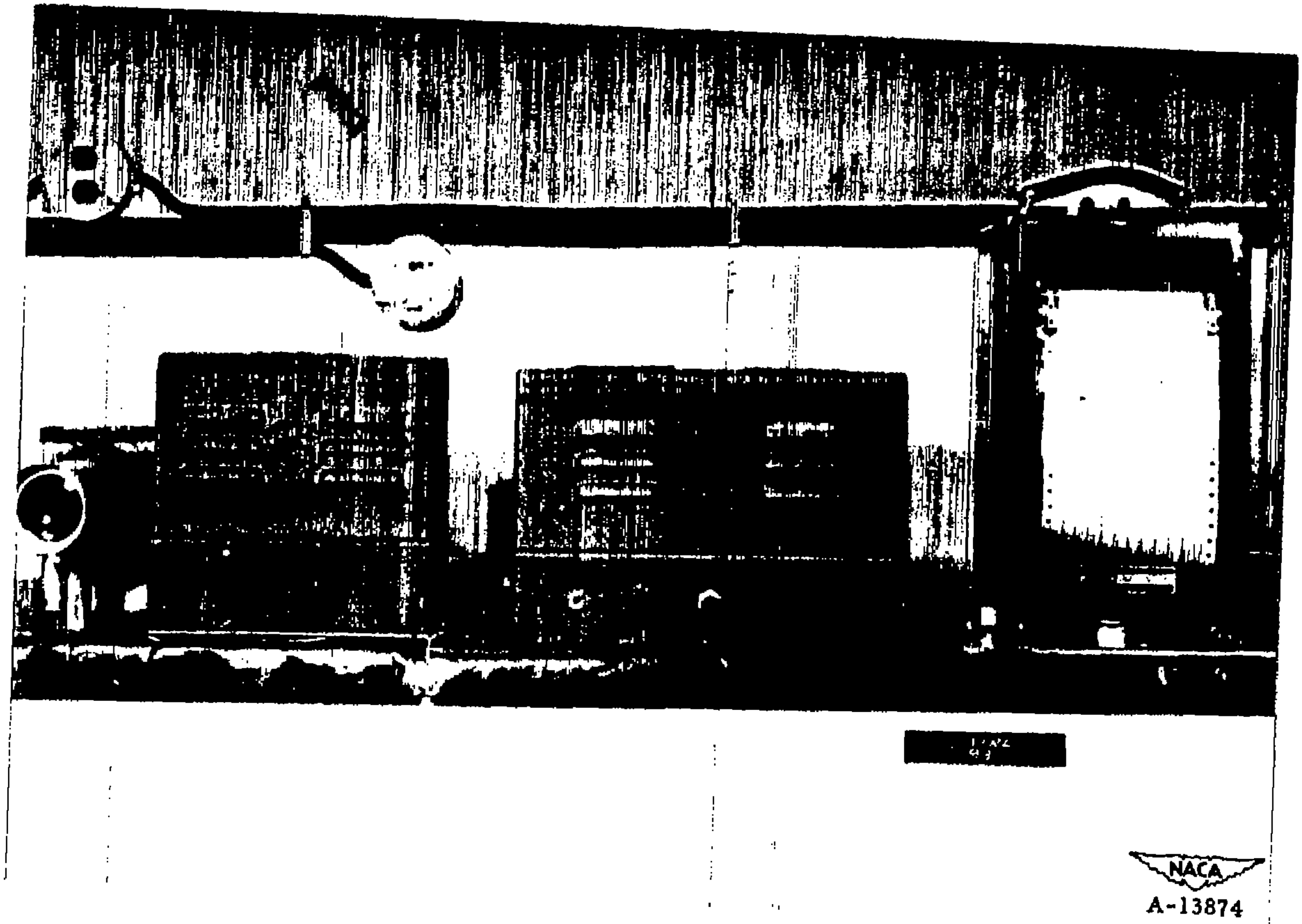
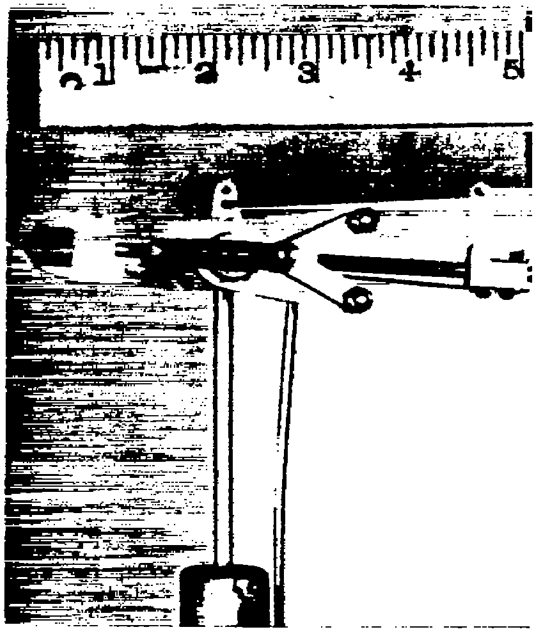
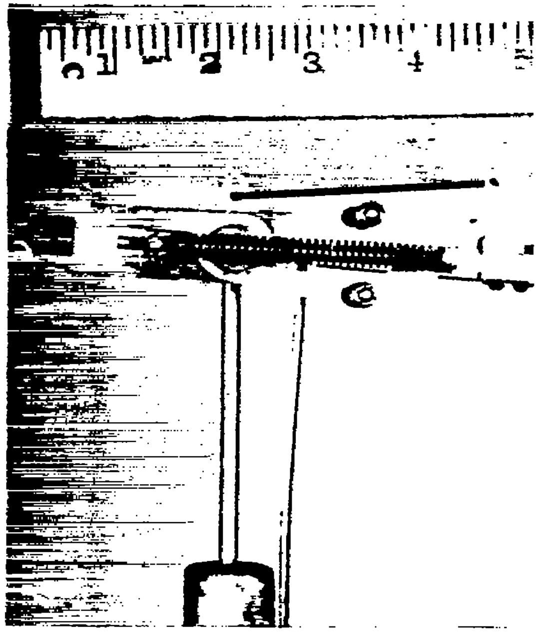


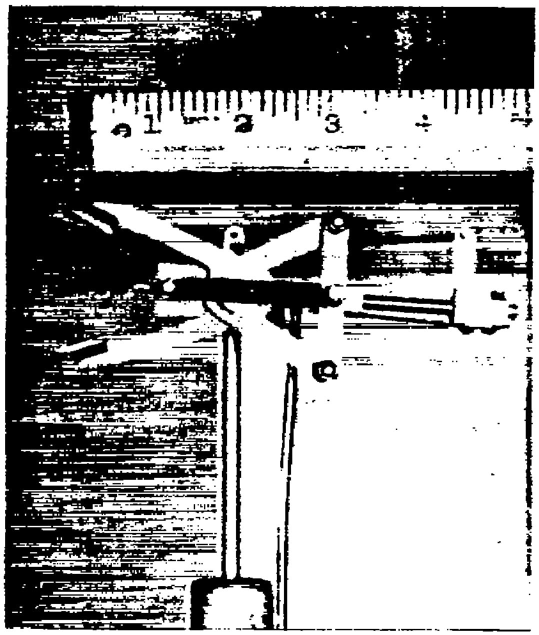
Figure 9.– Visibility indicator used to determine the ratio of average drop diameter to liquid-water content. Photograph reproduced from reference 13 through the courtesy of the U. S. Air Force.



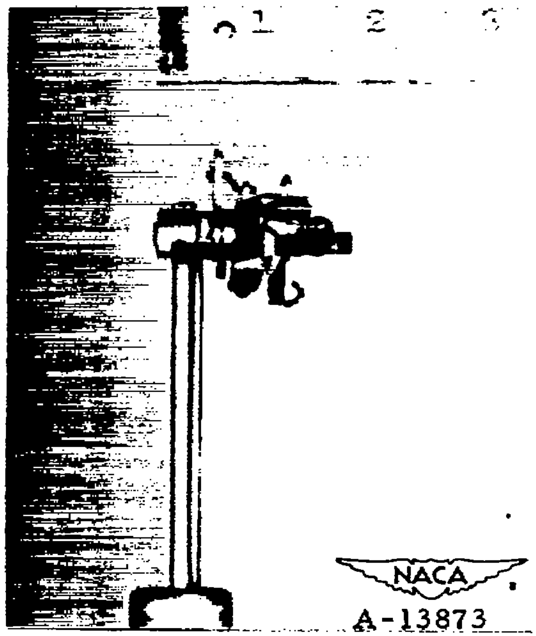
(a) Uncocked position.



(b) Cocked position.

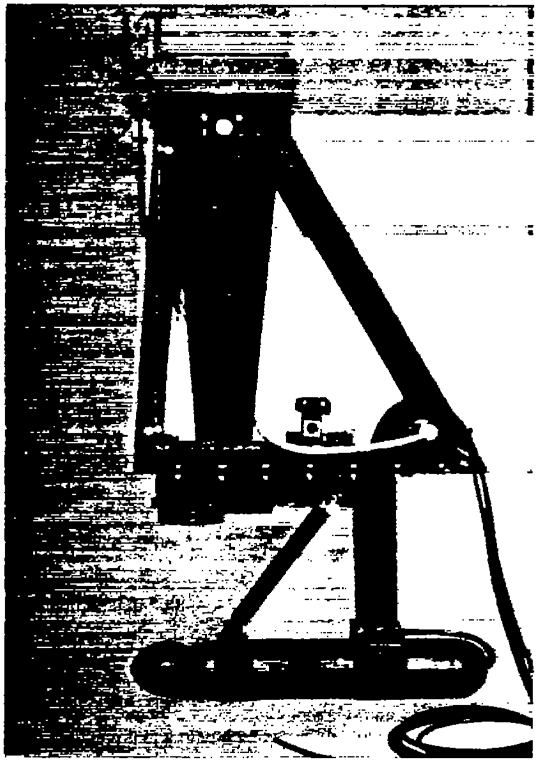


(c) Open position.

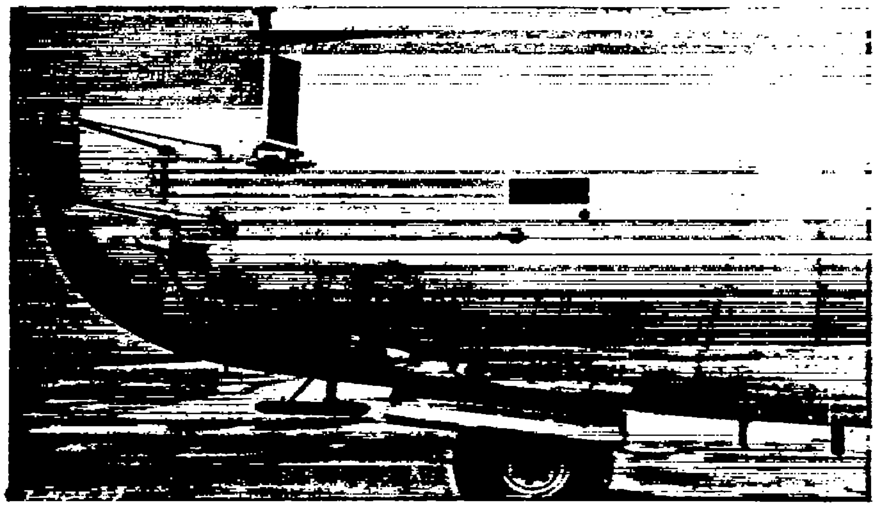


(d) Front view.

Figure 10.– Drop-size sampler employed for exposing soot-coated glass slides to an icing cloud during flight tests. Photograph supplied through the courtesy of the U. S. Air Force.



(a) Assembly.



(b) Camera installed on aircraft.

NACA
A-13875

Figure 11.– Camera developed for photographing cloud drops during flight. Photograph supplied through the courtesy of the National Research Council of Canada.